BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

SUBJECT: Requirement for an Oxygen Accumulator on AAP-2 - Case 620

DATE: October 1, 1968

FROM: W. W. Hough

ABSTRACT

An oxygen accumulator is required on the AAP-2 payload to augment oxygen flow from the Service Module cryogenic tanks and thus meet the requirements of extra vehicular activity and the Astronaut Maneuvering Unit experiment. The accumulator also permits pressure integrity checks of the AM and MDA prior to commitment of AAP-3A and AAP-3 CM-SM's to clustered missions. The Manned Spacecraft Center will recommend the use of two LM Descent Stage GOX tanks for the accumulator. The analysis documented in this memorandum supports that recommendation.

If the Service Module is equipped with Allis Chalmers, as opposed to uprated Pratt and Whitney fuel cells, the EVA and AMU requirements can be met with a single tank. In the event of a severe weight constraint on the AAP-2 payload, removal of one tank from the proposed system will result in a 58 pound dry-weight saving. However, confidence in a pressure integrity check would be diminished.

(NASA-CR-73566) REQUIREMENT FOR AN OXYGEN ACCUMULATOR ON AAP-2. CASE 620 (Bellcomm, Inc.) 12 p

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MEMORANDUM FOR FILE

A gaseous oxygen accumulator must be installed on AAP-2 because the oxygen flow rate requirements of emergency EVA operation and the M509 (Astronaut Maneuvering Unit) experiment exceed the maximum flow rate at which oxygen is available from the SM cryogenic storage system. Figure 1 is a simplified schematic diagram of the oxygen supply and distribution system being proposed by MSC.

SM SUPPLY

The maximum oxygen flow rate from the SM cryo tanks depends on the maximum heat input that the fuel cells can supply to the tanks. A Pratt and Whitney fuel cell configuration permits a maximum of 15 pounds per hour of oxygen to be delivered to the Airlock ECS. Because of the higher peak power capability of the Allis Chalmers fuel cells, up to 20 pounds per hour are available with this configuration. A flow limiting nozzle is installed in the CM-SM supply line to prevent excessive loss of oxygen in the event of a down-side line rupture. The nozzle also provides a constant flow rate with a constant supply pressure and with a pressure drop across the nozzle greater than about 47%*. The nozzle is sized for choked flow equal to 15 or 20 pounds/hour, depending on the fuel cell configuration, when the SM supply pressure is the minimum value of 850 psia.

EVA REQUIREMENTS

Flow rates requirements for EVA are based, in part, on the allowable concentration of carbon dioxide in an astronaut's helmet. The design limit on CO_2 concentration is 8 mm Hg. A flow rate of 7.9 pounds/hour of oxygen to the suit is required to maintain this level. The nominal rate is specified as 9.0 pounds/hour. During emergency EVA operation, when metabolic activity is greatly increased, a flow rate requirement of 13.7 pounds/hour is specified. A regulator in the pressure control unit (PCU or chest pack) can be adjusted by the astronaut to vary the rate from nominal to emergency if the situation demands it.

*See footnote to Appendix, page A-2

In the schematic of Figure 1, the EVA outlet shown is one of six, and the flow limiting nozzle is incorporated as a safety measure. If one EVA astronaut's umbilical is ruptured, the second EVA astronaut will not be starved of oxygen. This nozzle will be sized for choked flow of greater than the emergency rate at a minimum EVA supply pressure of about 100 psia.

The EVA time-line used for calculating accumulator requirements is two men for four hours, with one-half a man hour at the emergency rate. The total requirement is 74.35 pounds (3-1/2 hours at 18 pounds/hour and 1/2 hour at 22.7 pounds/hour).

As seen from Figure 1, the supply pressure to the EVA 120 psi regulators will nominally be 240 psi with the accumulator on line. Therefore, the supply rate from the SM can be the maximum. With the P & W fuel cell configuration, 60 pounds of oxygen can be supplied in the four hours, and the accumulator requirement is 14.35 pounds. With the A/C fuel cell system, the supply will be 18 pounds/hour when EVA operation is normal. But during the half hour of emergency operation, the difference between the 11.35 pound requirement and the maximum 10 pounds supplied, 1.35 pounds, must be supplied by the accumulator.

An EVA astronaut in AAP will carry an emergency oxygen supply strapped to his hip. This supply is 2.12 pounds, and can be used for a 10 minute period at the emergency rate. It could be used as a accumulator with the addition of a manually controlled regulator in the astronaut's PCU and meet the accumulator requirement for emergency EVA on an umbilical from a 20 pound/hour system. However, if the astronauts umbilical failed after the expenditure of 1.35 pounds, the remaining 0.77 pounds will last only about 3 minutes. This is insufficient time for the astronaut to reach another oxygen supply.

EXPERIMENT REQUIREMENTS

The M509 experiment requires very high instantaneous delivery rates (up to 360 lb/hr for 3 seconds), high average rates during periods of sustained operation (30.7 lb/hr average for 9 minutes), and an average rate of 20.2 pounds/hour over each experiment period. There are four periods of expermentation, two of which are divided into segments of suited and non-suited operation. During the suited segment of these periods, the 9 pound/hour suit requirement must be met in addition to the experiment requirement. The third period is the critical one from the accumulator standpoint; it requires 45 minutes of non-suited operation and 40 minutes of suited operation. There is a space of about half an hour between the non-suited and suited segments, and with either fuel cell configuration, the accumulator can be filled during this time. The 40 minute suited segment of the third period therefore dictates the maximum accumulator requirement.

The total oxygen requirement during the critical M509 period is 19.46 pounds. If the schematic of the system was as shown in Figure 2, where the down-stream pressure is regulated to 360 psia, the choked maximum flow could be delivered by the CM-SM and the accumulator requirement would be 9.46 pounds with Pratt and Whitney fuel cells and 6.13 pounds with Allis Chalmers fuel cells.

However, with the proposed system shown in Figure 1, all flow will come from the accumulator at the beginning of the period. This is because the accumulator, having just been filled by the SM, is at the same pressure as the supply and there is no pressure drop across the CM-SM nozzle. Choked flow across this nozzle will not occur until 47% of the accumulator supply has been used. The quantity delivered by the SM therefore depends not only on the maximum SM supply rate, but also on the size of the accumulator. It is a complex problem to determine the required capacities of the accumulator for this proposed system, but simpler to check the adequacy of a given capacity. This has been done in the Appendix, using one or two of the existing LM Descent Stage GOX tanks.

PROPOSED ACCUMULATOR TANKS

The proposed tank for the AM oxygen accumulator is the LM Descent Stage GOX tank. This existing steel sphere is designed to hold 45 pounds of gaseous oxygen at 2750 psia operating pressure and weighs 58 pounds. But, in this application, it cannot be repressurized to more than the 850 psia delivery pressure of the SM cryo tanks. Its full capacity at this pressure and at the same temperature (70°F) is 13.9 pounds. However, the accumulator cannot be fully depressurized. To maintain flow through the first set of regulators of the proposed system (Figure 1), the minimum pressure is on the order of 300 psia. The usable capacity is therefore 9.0 pounds. With the alternate system shown in Figure 2, the minimum pressure is about 420 psia, and the usable capacity is 7.0 pounds. The capability of the proposed system with one or two tanks to support the M509 experiment has been calculated in the Appendix. The results are stated in terms of the time it takes for the accumulator pressure to drop to the 300 psia minimum. These times, which are equivalent to capacities, are summarized in Table I.

REQUIRED NUMBER OF TANKS

Table I gives a summary of requirements and shows the capacities of the number of tanks required to meet these requirements.

The first conclusion is that the alternate system offers no advantage. The decrease is usable oxygen due to the increase in minimum accumulator pressure is a greater loss than the total not usable from the SM with the proposed system. The alternate system has the disadvantage of added plumbing valves, and regulators. Therefore, the proposed system is the proper selection.

With a 15 pound/hour choked-flow rate from the SM, two accumulator tanks are required to meet EVA and M509 oxygen requirements. With a 20 pound/hour rate, one tank is sufficient for these requirements. However, two tanks are desirable (except for the 58 pound weight penalty) for two reasons. First, the capability of one tank to support M509 is marginal--tolerances on the CM-SM flow-limiting nozzle could result in a deficiency. Second, the accumulator can be used for a pressure integrity check of the AM and MDA prior to committing a manned vehicle to clustered mission. A single tank with 9 pounds usable oxygen will provide a internal AM-MDA pressure of only 0.86 psia. Twice the capacity will permit twice the pressure, or 1.72 psia. The lower pressure does not give as good a check on the pressure shell integrity as does the upper. For these reasons, and because of uncertainty in the final SM fuel cell configuration, MSC will recommend a two-tank accumulator system for the Airlock Module. This author concurs with that recommendation. In the event of severe weight constraints on AAP-2, and if the SM is equipped with Allis Chalmers fuel cells, one tank can be removed for a saving of 58 pounds dry-weight, but confidence in pressure integrity checks for AAP-3A and AAP-3/AAP-4 missions will be sacrificed.

William W Hough

1022-WWH-bjw W. W. Hough

Attachment
- Appendix
- Figures 1-2
- Table I
- Table A-I

APPENDIX

Accumulator Capabilities to Support Experiments

The required average oxygen flow rate for the 40 minute suited portion of M509 Run 3 was stated in the text as 29.2 pounds/hour. The accumulator must provide that portion of the flow not provided by the CM-SM. With the proposed system (Figure 1 of text), a full accumulator will prevent any flow for the CM-SM. Maximum flow from the CM-SM will not occur until the pressure drop across its nozzle reaches the critical value of 47%, or until 47% of the accumulator supply is expended. An accumulator capacity must therefore be given before it can be determined if that capacity is sufficient to meet requirements. In this Appendix, one and two of the proposed LM Descent Stage GOX tanks are examined against requirements for supplementing CM-SM flow through 15 and 20 pound/hour choked-flow nozzles.

Terminology

R_S = flow rate from CM-SM

R_A = flow rate from accumulator

P_S = CM-SM supply pressure = 850 psia

P_A = accumulator pressure

C_A = accumulator capacity at 850 psia

Q_A = quantity of oxygen in accumulator

A_{15} = coefficient of equation for subsonic flow through 15 lb/hr choked flow nozzle

A_{20} = coefficient of equation for subsonic flow through 20 lb/hr choked flow nozzle

K = 1.39, a constant ratio of specific heat capacities of oxygen (C_p/C_v)

We know that the combined flow rates must equal the demand rate, or

$$R_S + R_A = 29.2 \text{ lb/hr.} \qquad \text{(A-1)}$$

The subsonic flow rate across the CM-SM nozzle is

$$R_S = A_M \left[\left(\frac{P_A}{P_S}\right)^{\frac{2}{K}} - \left(\frac{P_A}{P_S}\right)^{\frac{K+1}{K}} \right]^{1/2} \tag{A-2}$$

The coefficient A_M is obtained by setting R_S equal to the maximum for which the nozzle is sized, and the pressure ratio, $P_A/P_S = 0.53$.* This calculation yields

$$A_{15} = 58.633 \text{ lb/hr.}$$

$$A_{20} = 78.177 \text{ lb/hr.}$$

P_A is proportional to the quantity of gas remaining in the accumulator

$$P_A = \frac{P_S}{C_A} Q_A \tag{A-3}$$

and this quantity at any time T is equal to

$$Q_A(T) = C_A - \int_0^T R_A(t)dt \tag{A-4}$$

It is possible to combine equations (A-1) through (A-4) to give an integral equation in terms of $Q_A(t)$, but care must be taken in the time of transition from subsonic to sonic flow. A simpler

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*This critical pressure ratio is derived by maximizing R_S and solving for P_A/P_S. The velocity at the throat of the nozzle with this pressure ratio is equal to the velocity of sound in the flowing medium, and there are no flow discontinuities within the nozzle. At lower pressure ratios, flow discontinuities (shock) will occur within the divergent section of the nozzle, but the velocity at the throat will not exceed the sonic velocity. Therefore, at pressure ratios lower than the critical, the flow will remain constant - this is called choked flow. For a complete discussion of variable-area compressible flow, including a derivation of (A-2), see:

Cambel, A. B. and Jennings, B. H., Gas Dynamics, McGraw Hill Book Co., Inc., New York, 1958, Ch. 7.

method of checking whether a given accumulator will meet the requirement for M509 is to calculate, by a form of numerical integration, the time it will take to reach the minimum pressure at which it will supplement the CM-SM flow. This is done in Tables A-I and A-II for the two cases of maximum flow and for the two sizes of accumulators.

The increment used is a pressure drop of 50 psi in the accumulator. For each accumulator pressure, the flow from the CM-SM is calculated by (A-2) and the flow from the accumulator by (A-1). The average accumulator rate during the increment of pressure drop is then divided into the change in quantity, which is found directly from (A-3) using a capacity of 13.9 pounds for one Descent Stage GOX tank at 850 psia, and twice that for two tanks. This yields a slightly conservative time for the 50 psi accumulator pressure drop (conservative in that the average SM rate during the increment is slightly higher than the numerical average between the rates at the beginning and end of each increment; therefore the average accumulator rate requirement is less than that given, and the actual time to drop an increment is slightly greater than given). When the accumulator pressure reaches 450 psia, choked flow of the nozzle occurs (.53 x 850 = 450), and the accumulator supplies 29.2 minus the CM-SM maximum. The minimum accumulator pressure is taken at 300 psia to maintain flow across the M509 regulators (Figure 1 of text). The total time to reach this minimum accumulator pressure is the sum of the time increments for each pressure drop, and if this time is greater than the 40 minute running time of the experiment, the accumulator has sufficient capacity to meet the requirements. In the case of a 15 pound/hour maximum CM-SM flow rate, a one tank system would be exhausted in about 33 minutes, so a two tank system, which gives over an hour, is required. In the case of a 20 pound/hour maximum CM-SM flow rate, a one tank system will last for 47.6 minutes, which is marginally sufficient.

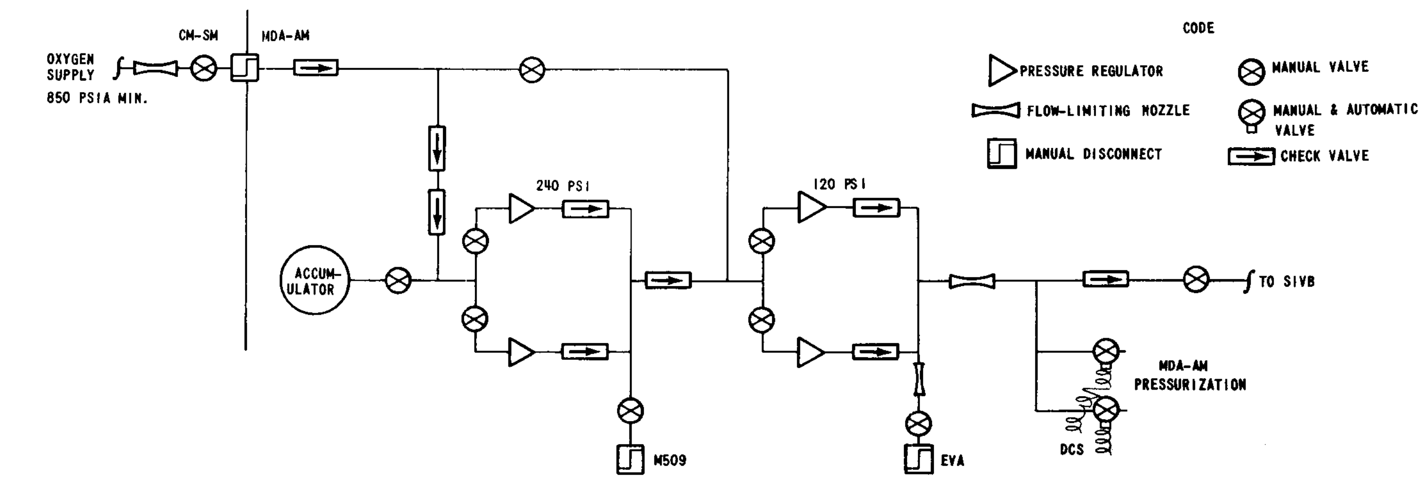

FIGURE 1 - PROPOSED SCHEMATIC

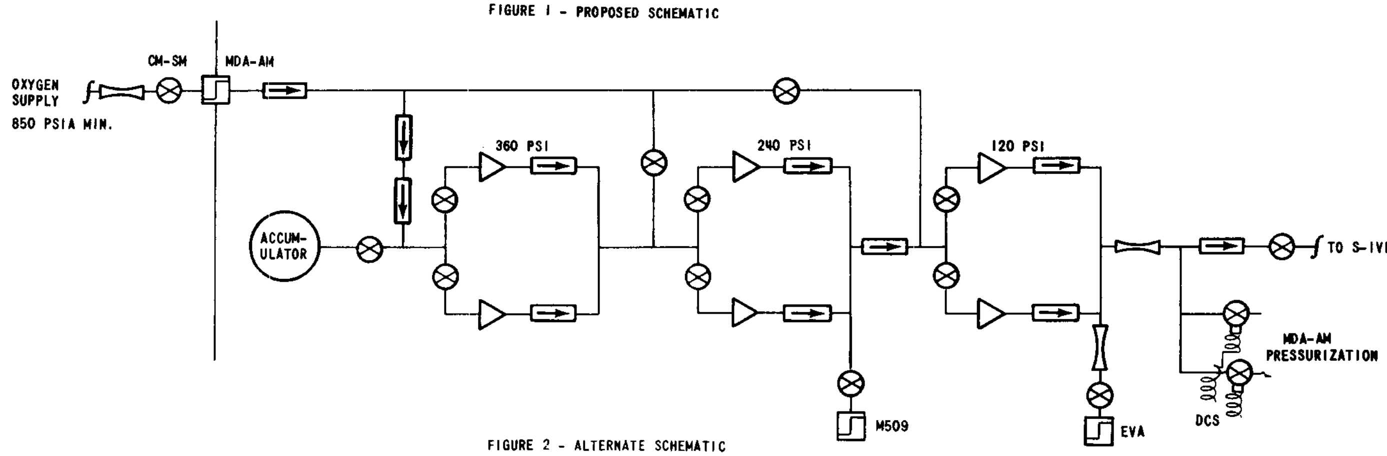

FIGURE 2 - ALTERNATE SCHEMATIC

TABLE I

SUMMARY OF REQUIREMENTS

	Maximum SM flow rate 15 lb/hr	Maximum SM flow rate 20 lb/hr
PROPOSED SYSTEM (FIG. 1)		
EVA Requirement	14.35 lbs	1.35 lbs
EVA Required Tanks	2 Tanks = 18 lbs	1 Tank = 9 lbs
M509 Requirement	40 min	40 min
M509 Required Tanks	2 Tanks = 66.9 min	1 Tank = 47.6 min
Number of Tanks Required	2 Tanks	1 Tank
ALTERNATE SYSTEM (FIG. 2)		
EVA Requirement	14.35 lbs	1.35 lbs
EVA Required Tanks	3 Tanks = 21 lbs	1 Tank = 6 lbs
M509 Requirement	9.46 lbs	6.13 lbs
M509 Required Tanks	3 Tanks = 14 lbs	1 Tank = 7 lbs
Number of Tanks Required	3 Tanks	1 Tank

Table A-I

Accumulator Use - Maximum Flow Rate from SM = 15 pounds/hour

				C_A = 13.9 lb			C_A = 27.8 lb		
P_A	R_S	R_A	Avg. R_A	ΔQ_A	Δt	t	ΔQ_A	Δt	t
(psia)	(lb/hr)	(lb/hr)	(lb/hr)	(lb)	(hr)	(hr)	(lb)	(hr)	(hr)
850	0	29.200				0			0
			25.556	.81765	.03199		1.63530	.06399	
800	7.289	21.911				.03199			.06399
			20.578		.03973			.07947	
750	9.954	19.246				.07173			.14346
			18.352		.04455			.08911	
700	11.741	17.459				.11628			.23256
			16.821		.04861			.09722	
650	13.017	16.183				.16489			.32978
			15.729		.05177			.10355	
600	13.925	15.275				.21666			.43333
			14.969		.05463			.10925	
550	14.536	14.664				.27129			.54258
			14.488		.05643			.11287	
500	14.887	14.313				.32772			.65545
			14.256		.05736			.11471	
450	15.000	14.200				.38508			.77016
			14.200	2.45295	.17274		4.90590	.34548	
300	15.000	14.200				.55782			1.11564
						= 33.5 min			= 66.9 min

Table A-II

Accumulator Use - Maximum Flow Rate from SM = 20 pounds/hour

P_A	R_S	R_A	Aug. R_A	C_A = 13.9 lb			C_A = 27.8 lb		
				ΔQ_A	Δt	t	ΔQ_A	Δt	t
(psia)	(lb/hr)	(lb/hr)	(lb/hr)	(lb)	(hr)	(hr)	(lb)	(hr)	(hr)
850	0	29.200				0			0
			24.341	.81765	.03359		1.63530	.06718	
800	9.719	19.481				.03359			.06718
			17.705		.04618			.09236	
750	13.272	15.928				.07977			.15954
			14.737		.05548			.11096	
700	15.654	13.546				.13526			.27051
			12.695		.06441			.12881	
650	17.356	11.844				.19966			.39932
			11.238		.07276			.14552	
600	18.567	10.633				.27242			.54484
			10.226		.07996			.15992	
550	19.381	9.819				.35238			.70476
			9.585		.08530			.17060	
500	19.849	9.351				.43768			.87536
			9.276		.08815			.17630	
450	20.000	9.200				.52583			1.05166
			9.200	2.45295	.26662		4.90590	.53325	
300	20.000	9.200				.79245			1.58491
						= 47.6 min			= 95.1 min.